Searching for CPV induced sphaleron process at the early Universe with Magnetic Field observations

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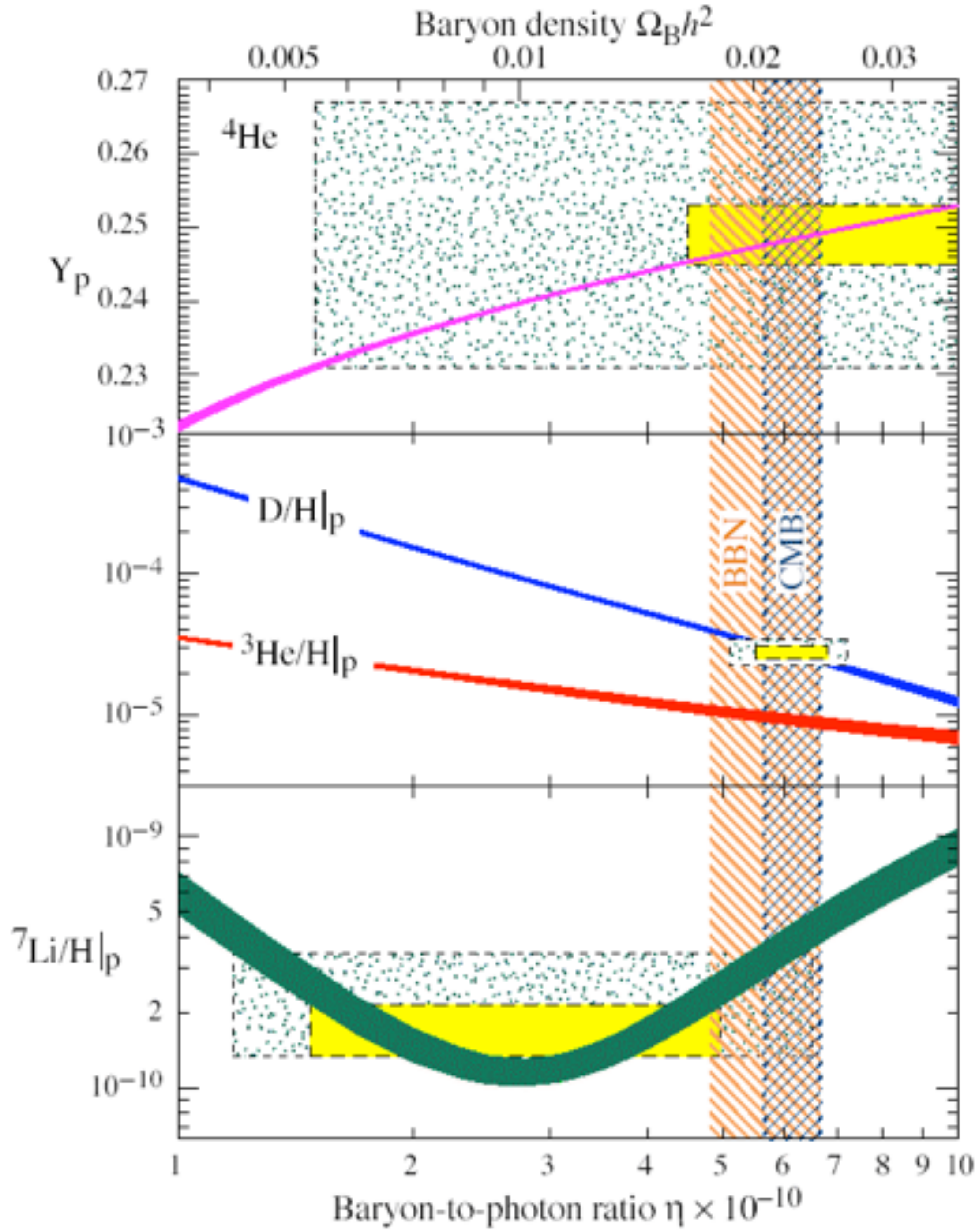
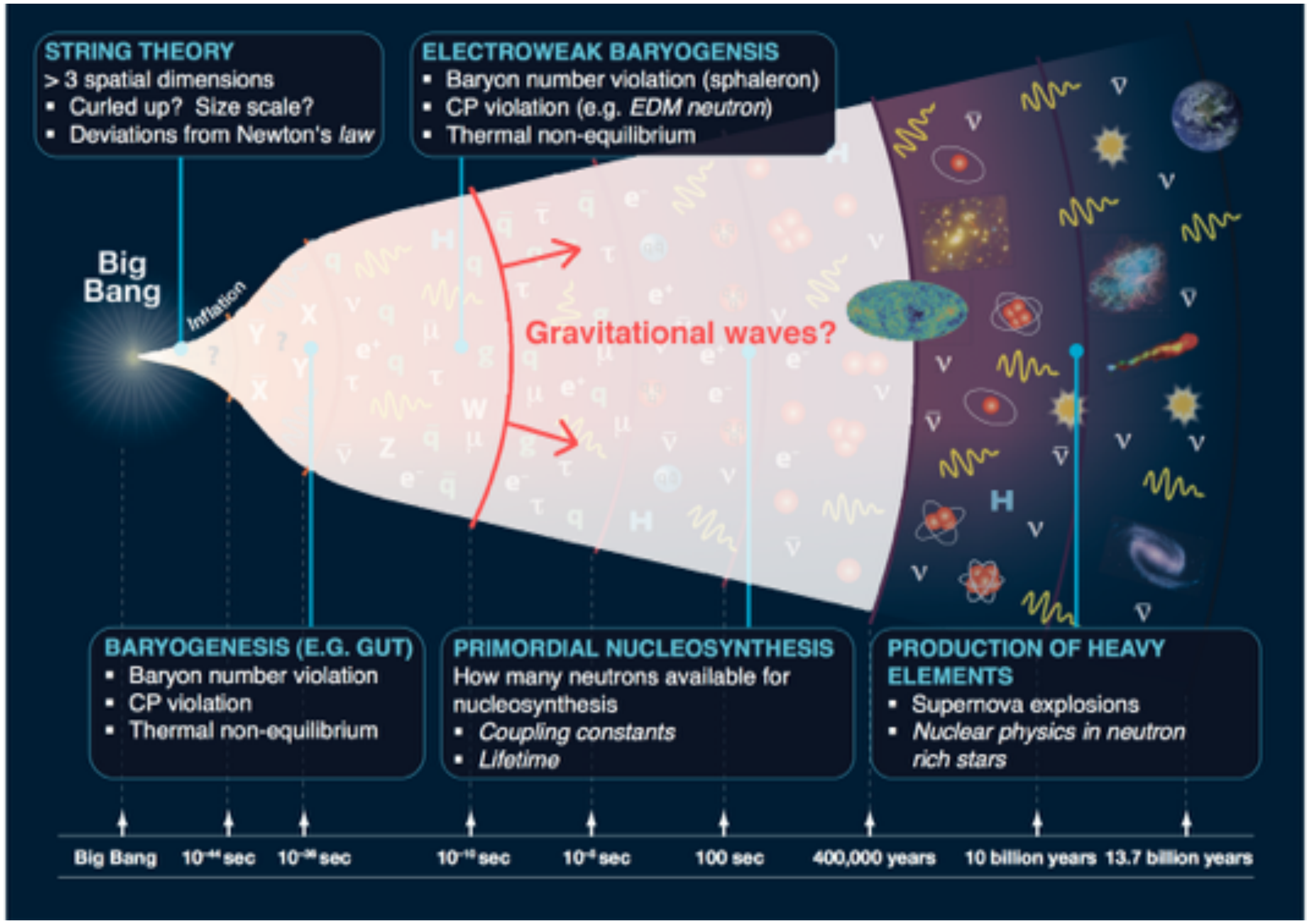
HFCPV2021, 11/10-11/14, 2021

Outline

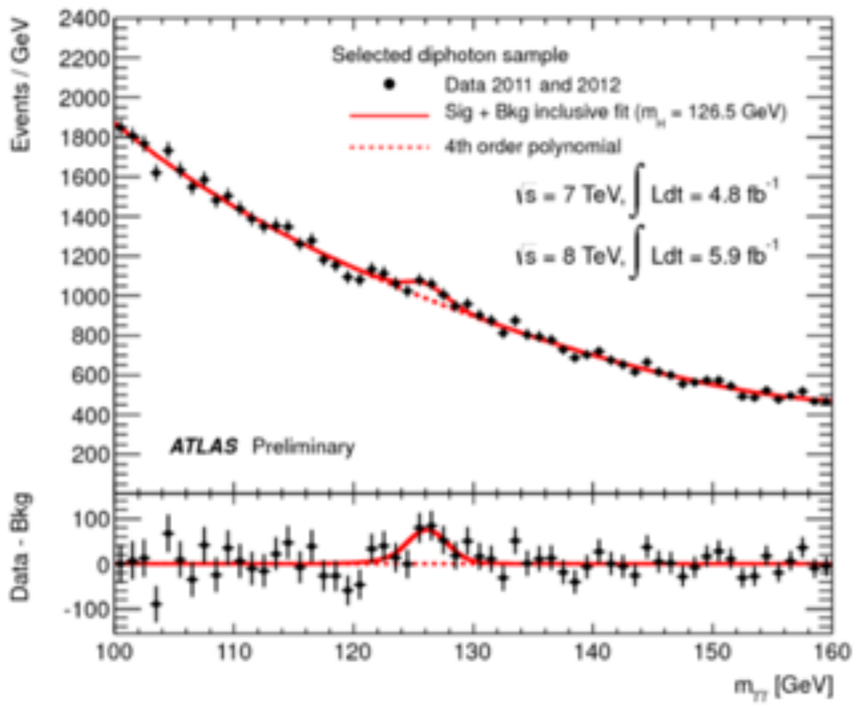
- **First-order phase transition**
- **CPV and BAU**
- **Sphaleron search**
- **Future prospect**

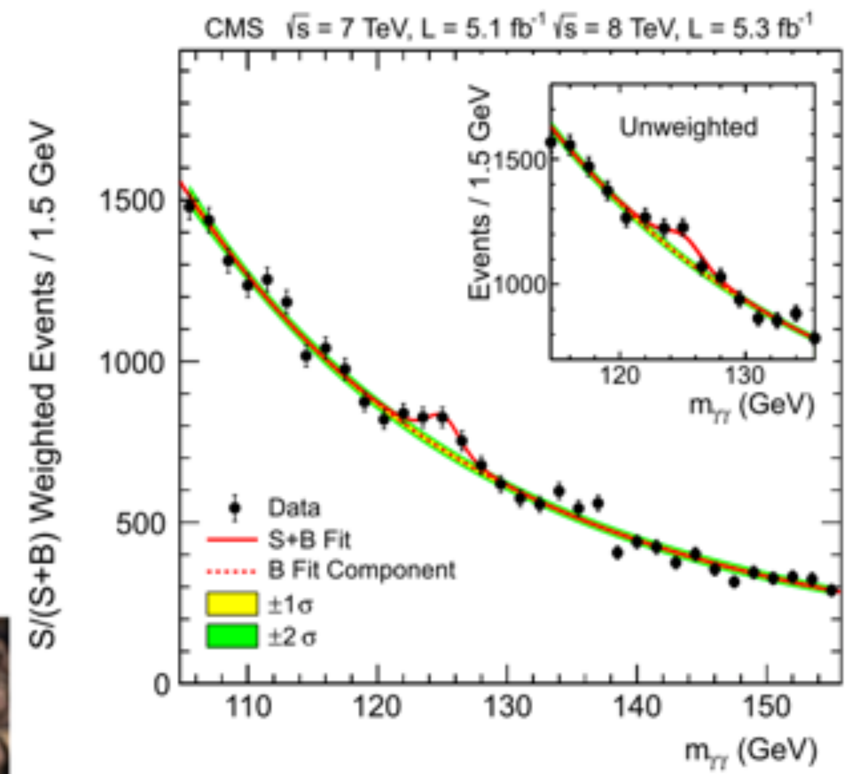
Baryon Asymmetry of the Universe



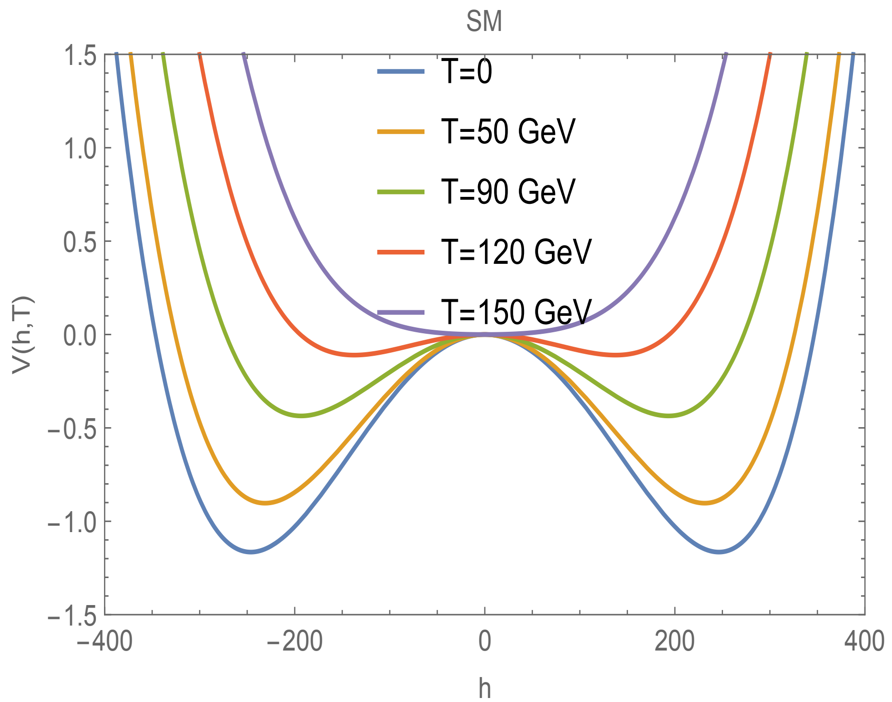


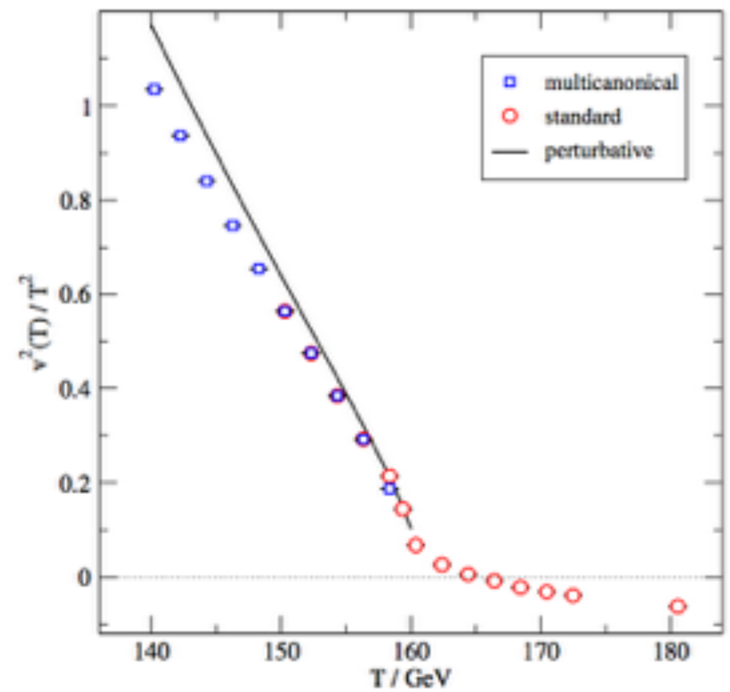
Implication of 125 GeV Higgs





Higgs announcement seminar on 4 July 2012

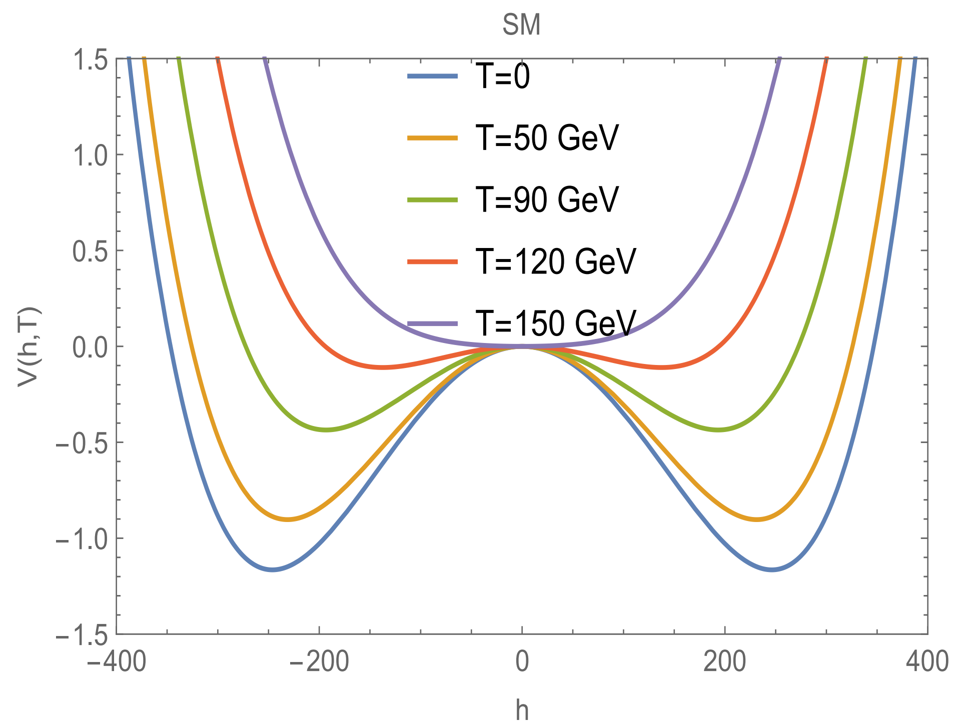


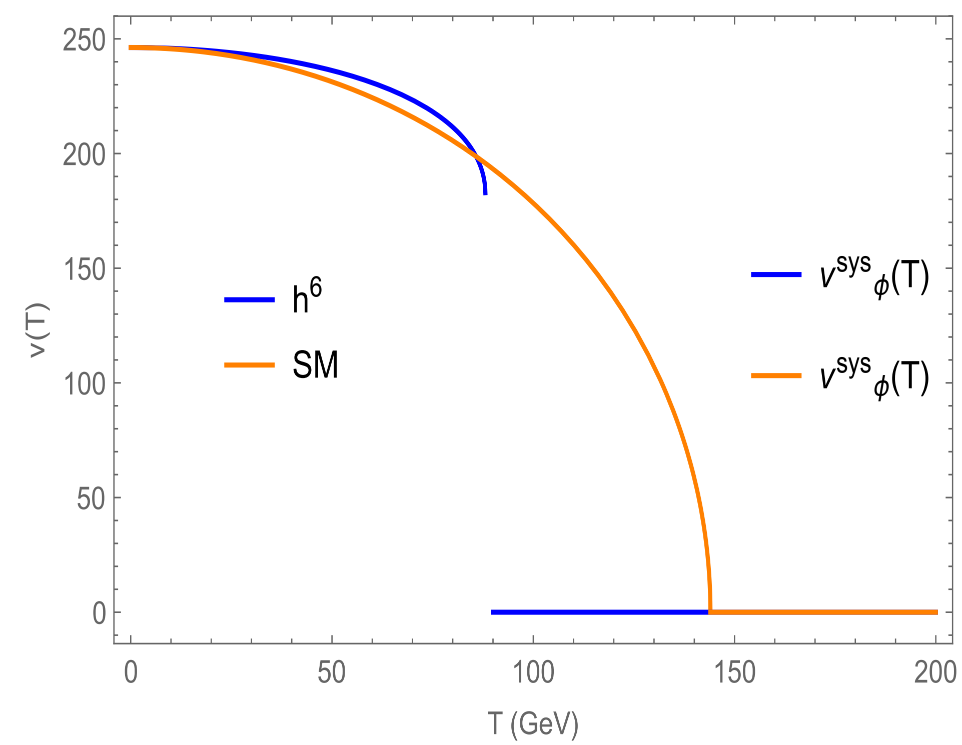


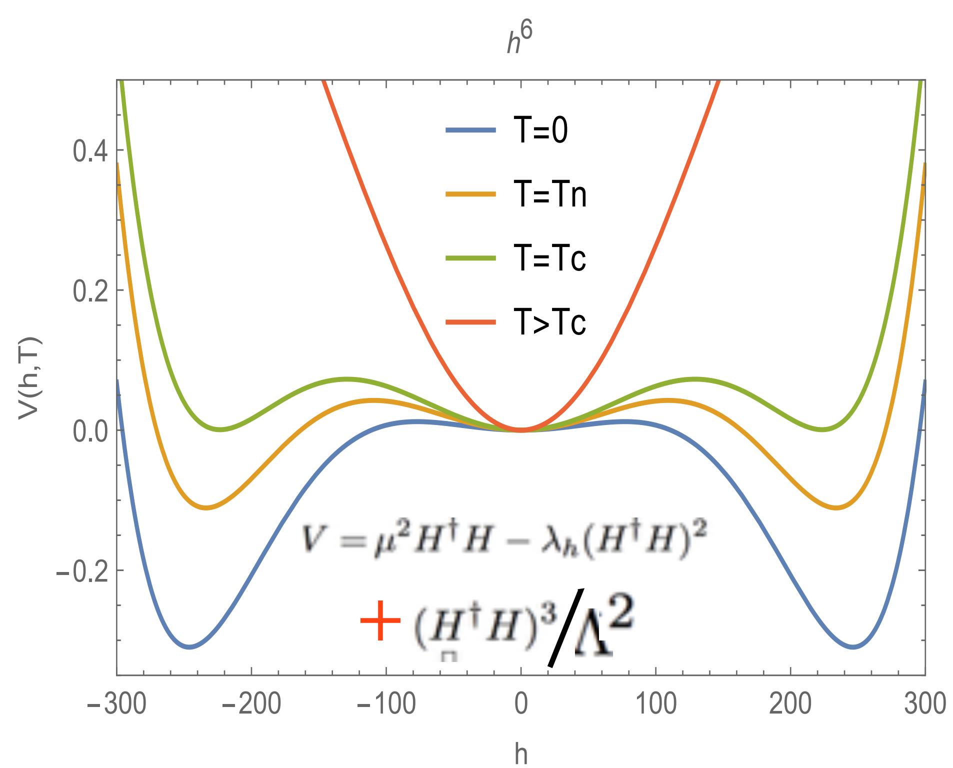
PRL 113, 141602 (2014)

Higgs Potential Shape??? EFT or ???

First or second order





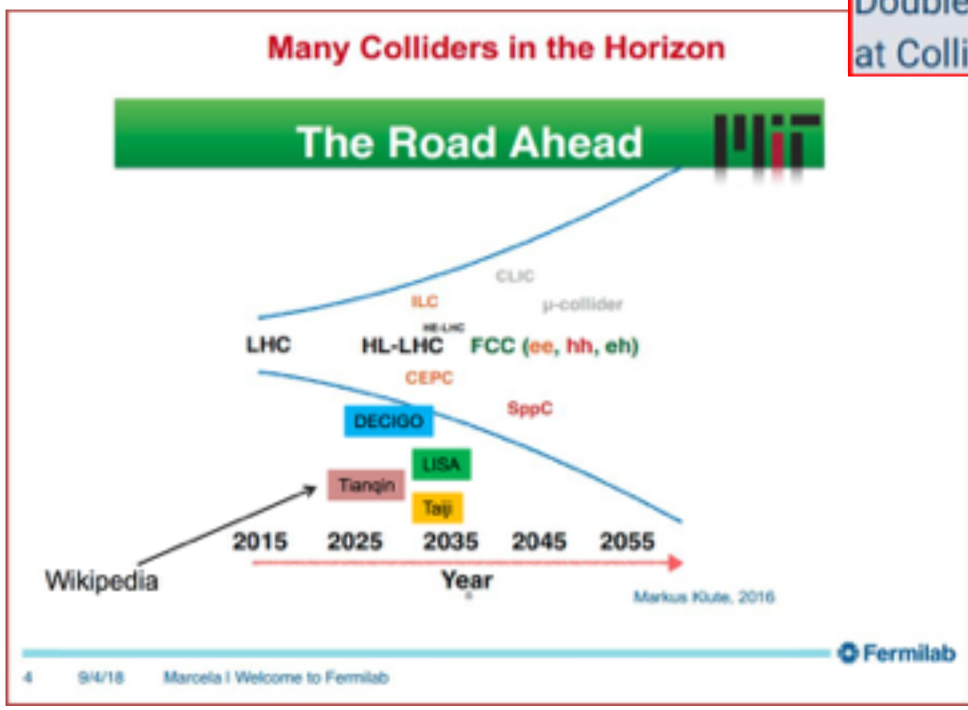


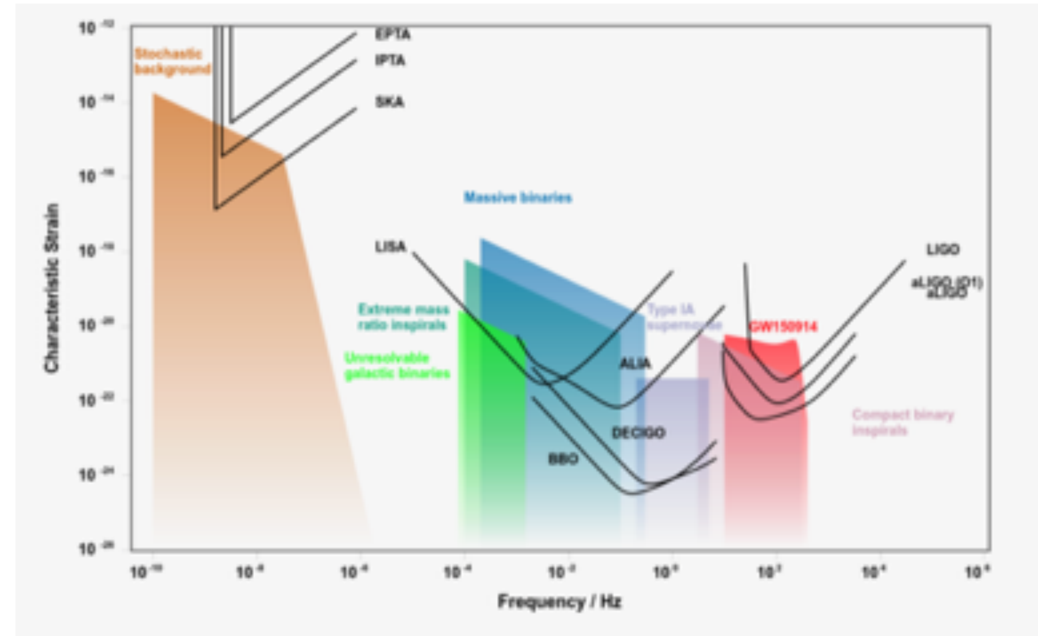
Grojean, Servant, Wells 05, P. Huang, Jokelar, Li, Wagner 15,Cao, F.P. Huang, Xie, & Zhang 17, Zhou, **Bian**, Guo 19

LHC say the quantum fluctuation (quadratic oscillation) around h=v with mh=126 GeV, not sensitive to the specifically potential shape

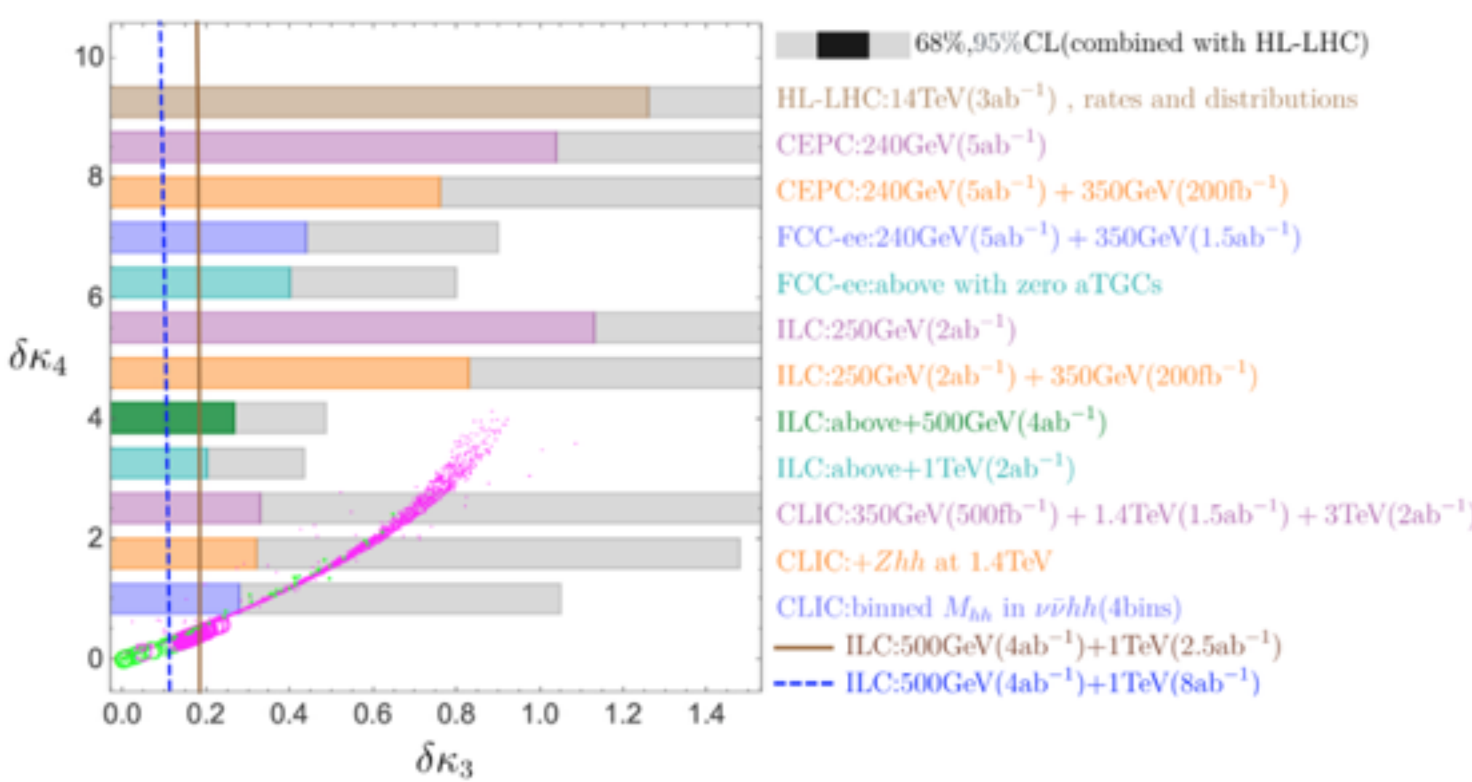
PTGW and collider search

Double Higgs Production at Colliders Workshop





C J Moore et al. Class. Quantum Grav. 32 (2015) 015014.



$$\Delta\mathscr{L} = -\frac{1}{2}\frac{m_h^2}{v}(1+\delta\kappa_3)h^3 - \frac{1}{8}\frac{m_h^2}{v^2}(1+\delta\kappa_4)h^4$$

SNR > 10 for two-step and one-step SFOEWPT

Bian, Guo, Wu, Zhou, Phys.Rev.D 101 (2020) 3, 035011

BSM for EWPT

- **SM+Scalar Singlet**

Espinosa, Quiros 93, Benson 93, Choi, Volkas 93, Vergara 96, Branco, Delepine, Emmanuel- Costa, Gonzalez 98, Ham, Jeong, Oh 04, Ahriche 07, Espinosa, Quiros 07, Profumo, Ramsey-Musolf, Shaughnessy 07, Noble, Perelstein 07, Espinosa, Konstandin, No, Quiros 08, Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy 09, Ashoorioon, Konstandin 09, Das, Fox, Kumar, Weiner 09, Espinosa, Konstandin, Riva 11, Chung, Long 11, Barger, Chung, Long, Wang 12, Huang, Shu, Zhang 12, Fairbairn, Hogan 13, Katz, Perelstein 14, Profumo, Ramsey-Musolf, Wainwright, Winslow 14, Jiang, **Bian,** Huang, Shu 15, Kozaczuk 15, Cline, Kainulainen, Tucker-Smith 17, Kurup, Perelstein 17, Chen, Kozaczuk, Lewis 17,Cheng, **Bian** 17, Bian, Tang 18,Chen, Li, Wu, **Bian**,19…

- **SM+Scalar Doublet**

Turok, Zadrozny 92, Davies, Froggatt, Jenkins, Moorhouse 94, Cline, Lemieux 97, Huber 06, Froome, Huber, Seniuch 06, Cline, Kainulainen, Trott 11, Dorsch, Huber, No 13, Dorsch, Huber, Mimasu, No 14, Basler, Krause, Muhlleitner, Wittbrodt, Wlotzka 16, Dorsch, Huber, Mimasu, No 17, Bernon, **Bian,** Jiang 17, **Bian**, Liu 18,…

- **SM + Scalar Triplet**

Profumo, Ramsey-Musolf 12, Chiang 14, Zhou, Cheng, Deng, **Bian**, Wu 18,Zhou, **Bian**, Guo,Wu 19,…

- **NMSSM**

Pietroni 93, Davies, Froggatt, Moorhouse 95, Huber, Schmidt 01, Ham, Oh, Kim, Yoo, Son 04, Menon, Morrissey, Wagner 04, Funakubo, Tao, Yokoda 05, Huber, Konstandin, Prokopec, Schmidt 07, Chung, Long 10, Kozaczuk, Profumo, Stephenson Haskins, Wainwright 15, Bi, **Bian**, Huang, Shu, Yin 15, **Bian,** Guo, Shu 17,…

- **Composite Higgs**

Espinosa, Gripaios, Konstandin, Riva 11, Bruggisser, Von Harling, Matsedonskyi, Servant 18, **Bian**,Wu,Xie 19, De Curtis, Delle Rose, Panico 19, **Bian**,Wu,Xie 20,…

- **EFT**

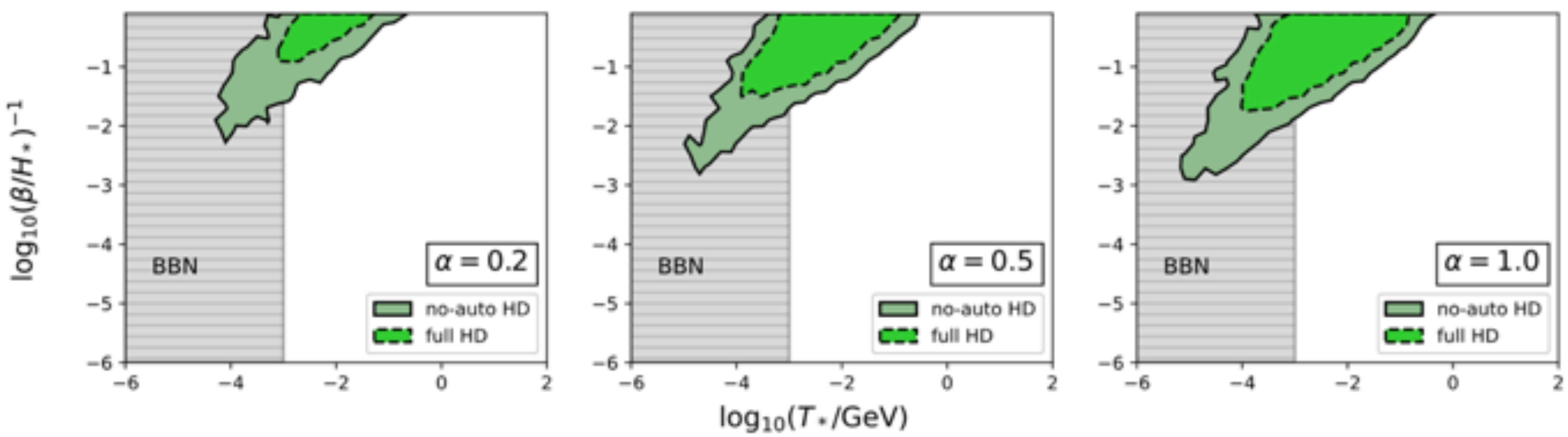
Grojean, Servant, Wells 05, Bodeker, Froome, Huber, Seniuch 05, Huang, Joglekar, Li, Wagner 15,Cai,Sasaki ,Wang17,Zhou, **Bian**, Guo 19, …

PTGW experimental constraints

Low-scale QCD&Dark PT

Xue, Bian*, Shu*, Yuan*, Zhu*, etal, 2110.03096, PRL in press, editor suggestion

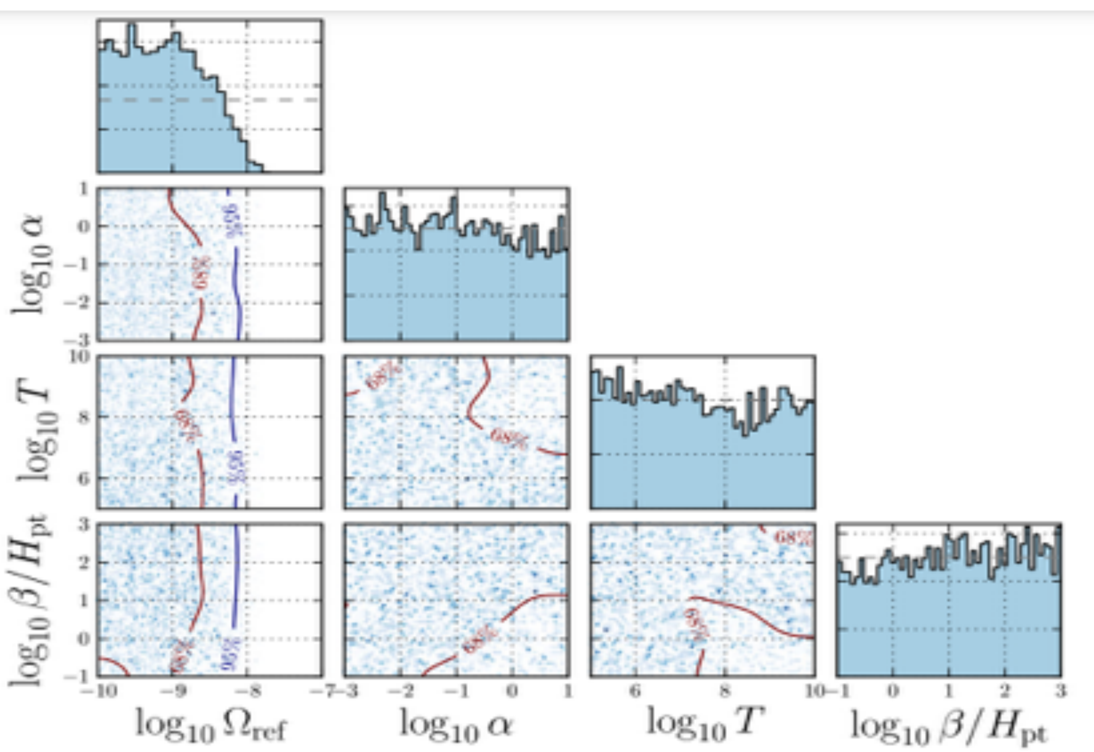
PPTA



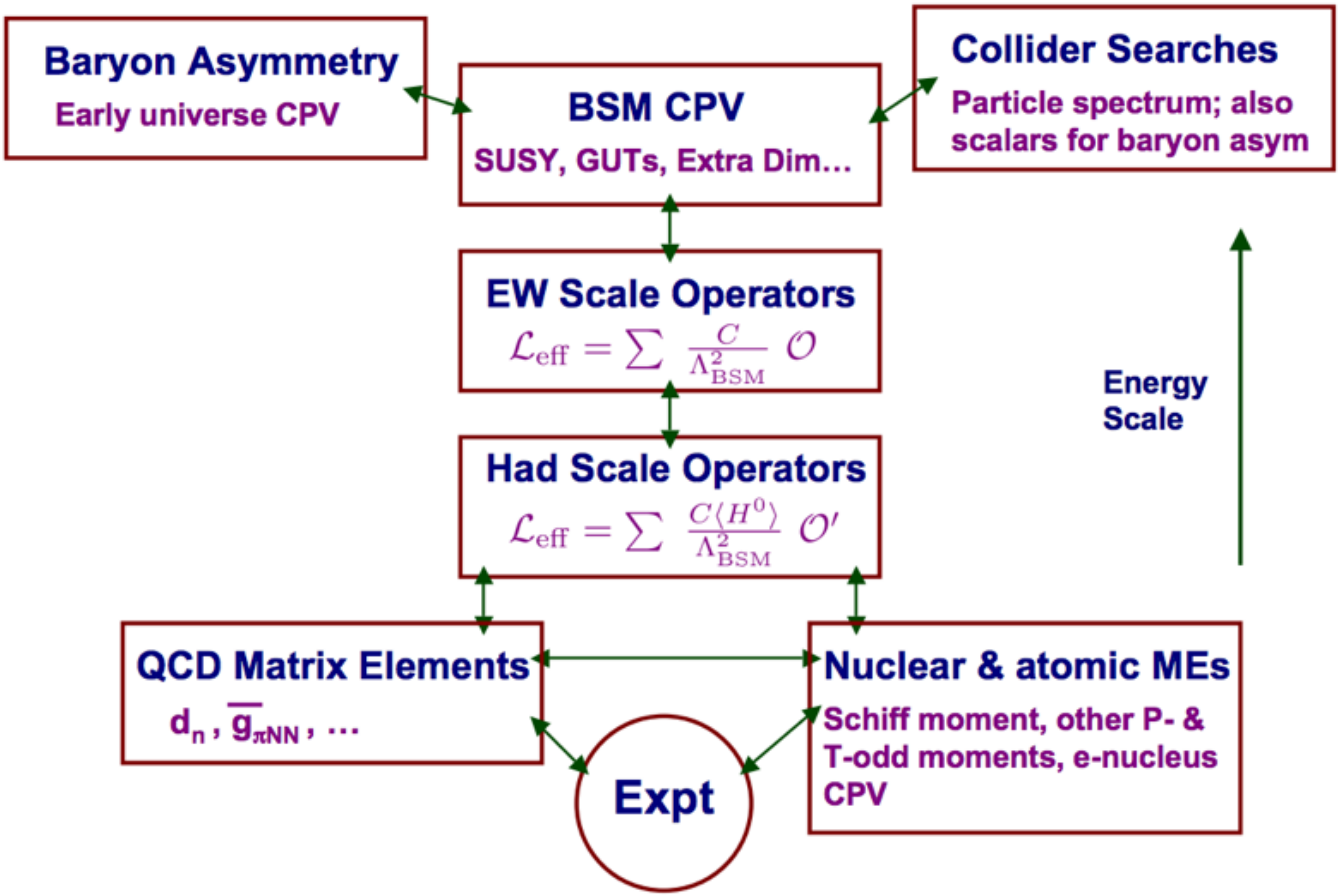
High-scale PT

Romero, Martinovic,Callister, Guo, et al., Phys.Rev.Lett. 126 (2021) 15, 151301

LIGO-Virgo O3

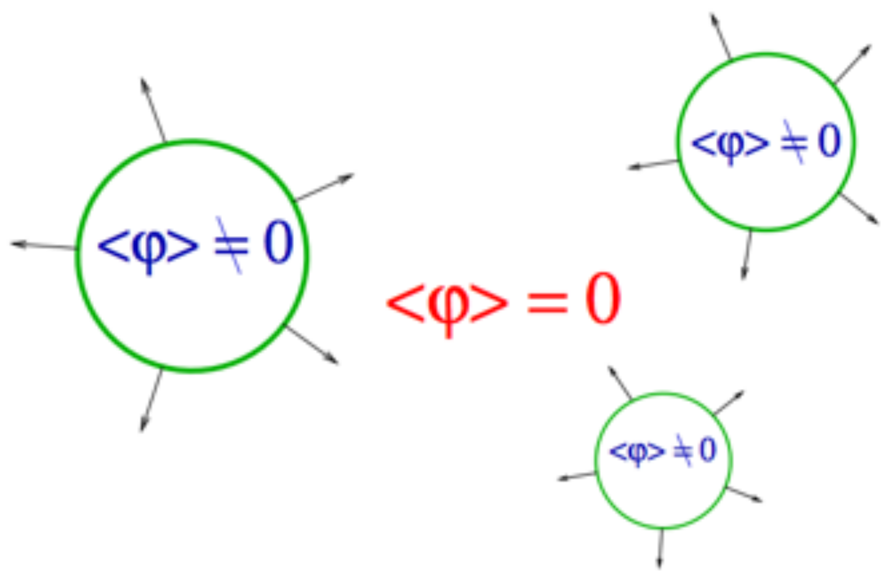


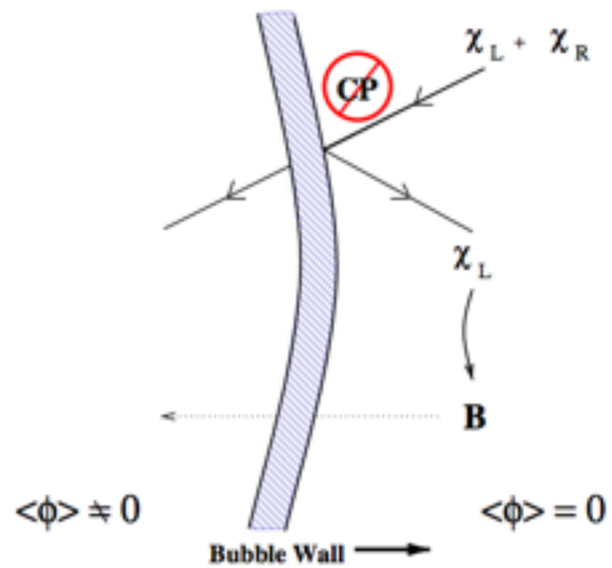
CPV and EDMs



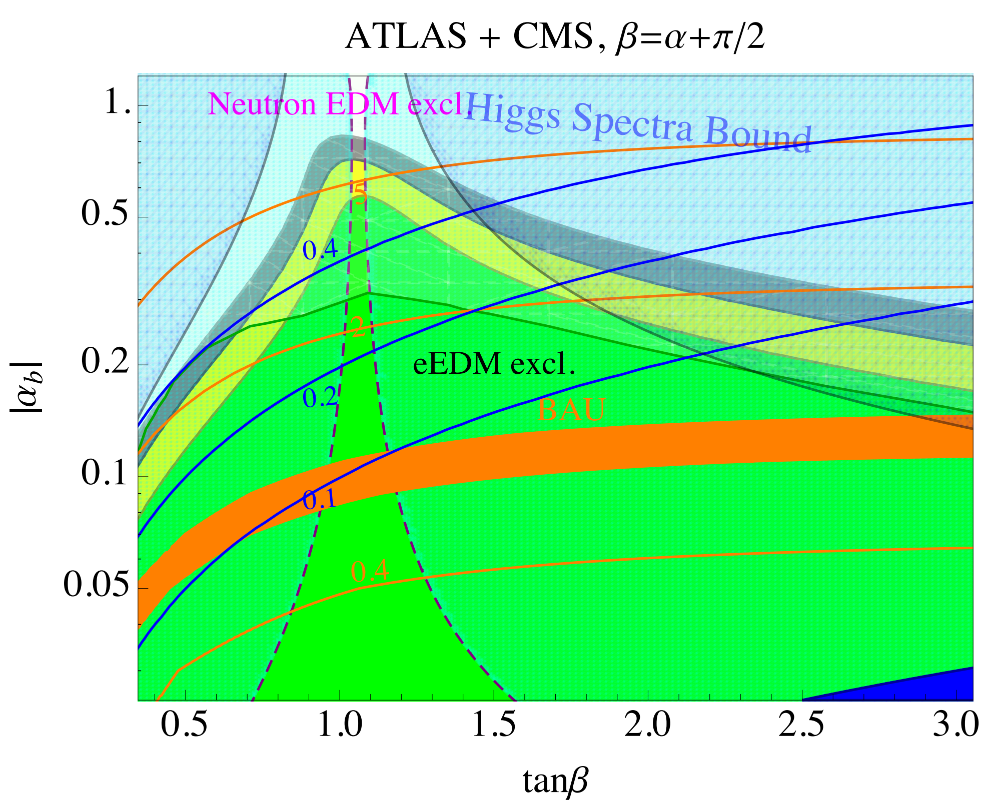
Engel etal, Prog.Part.Nucl.Phys. 71 (2013) 21-74

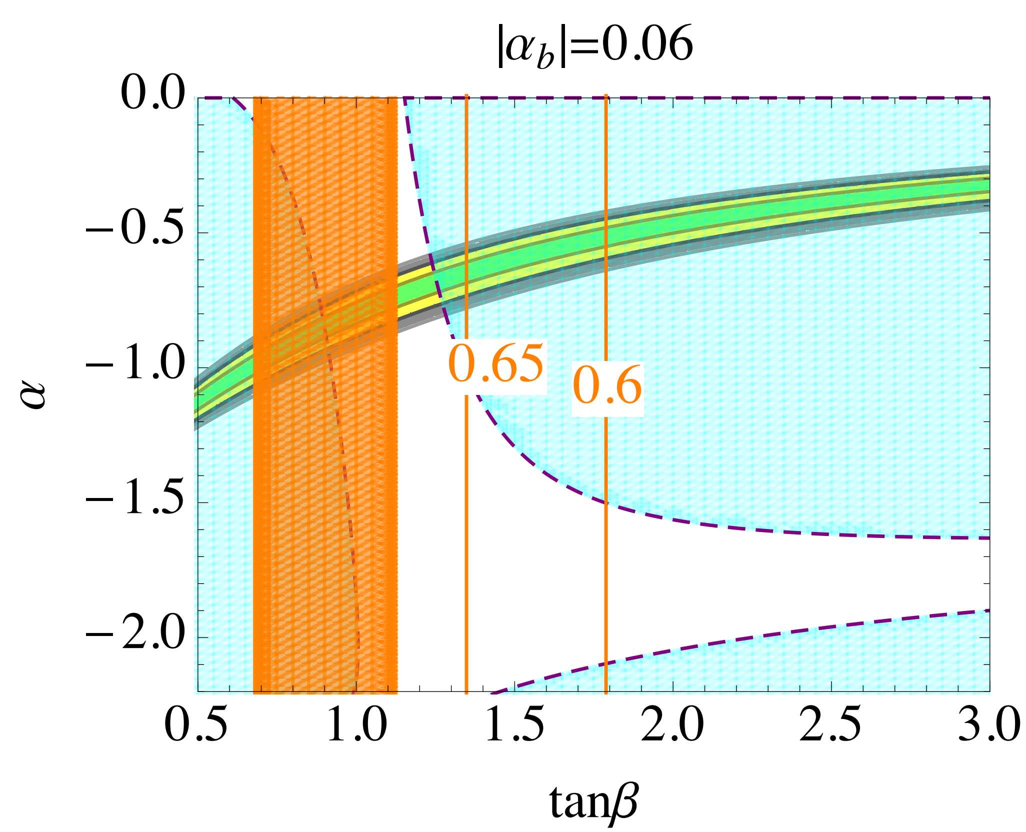
Electroweak Baryogenesis





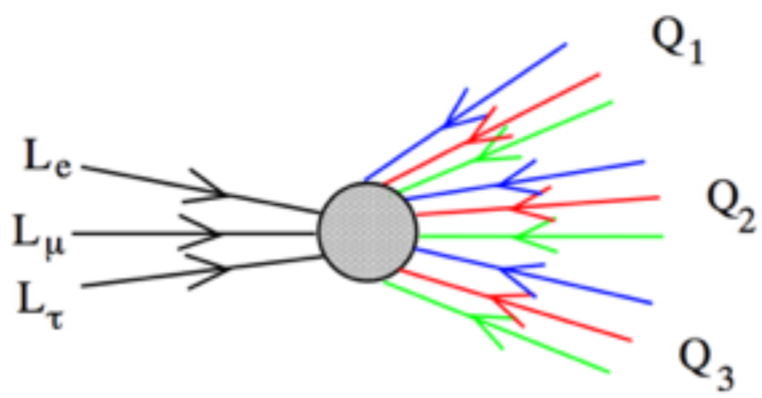
Chup etal, Rev Mod Phys.91.015001

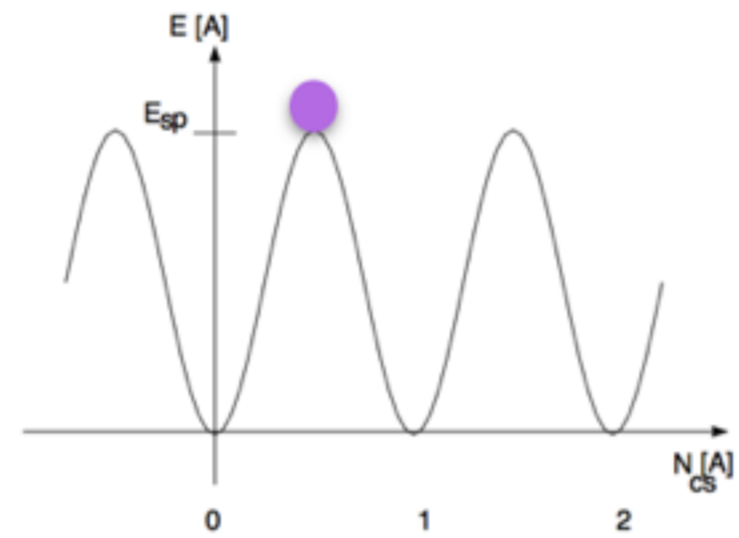




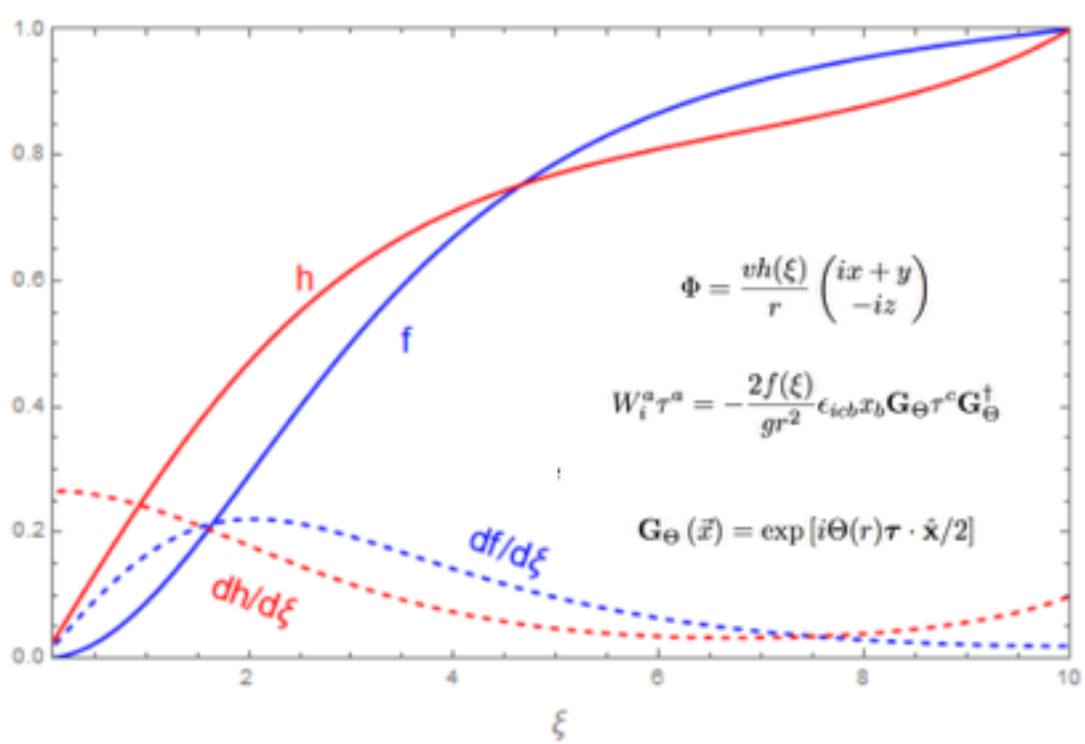
Bian, Liu, Shu, Phys.Rev.Lett. 115 (2015) 021801

The Standard Model already contains a process that violates B-number. It is known as the electroweak sphaleron ("sphaleros" is Greek for "ready to fall").





Klinkhammer & Manton (1984); Kuzmin, Rubakov, & Shaposhnikov (1985); Harvey & Turner (1990)
but also identified earlier by Dashen, Hasslacher, & Neveu (1974) and Boguta (1983)



$$\partial_\mu J_B^\mu = i\frac{N_F}{32\pi^2}\left(-g_2^2 F^{a\mu\nu}\widetilde{F}^a_{\mu\nu} + g_1^2 f^{\mu\nu}\widetilde{f}_{\mu\nu}\right),$$

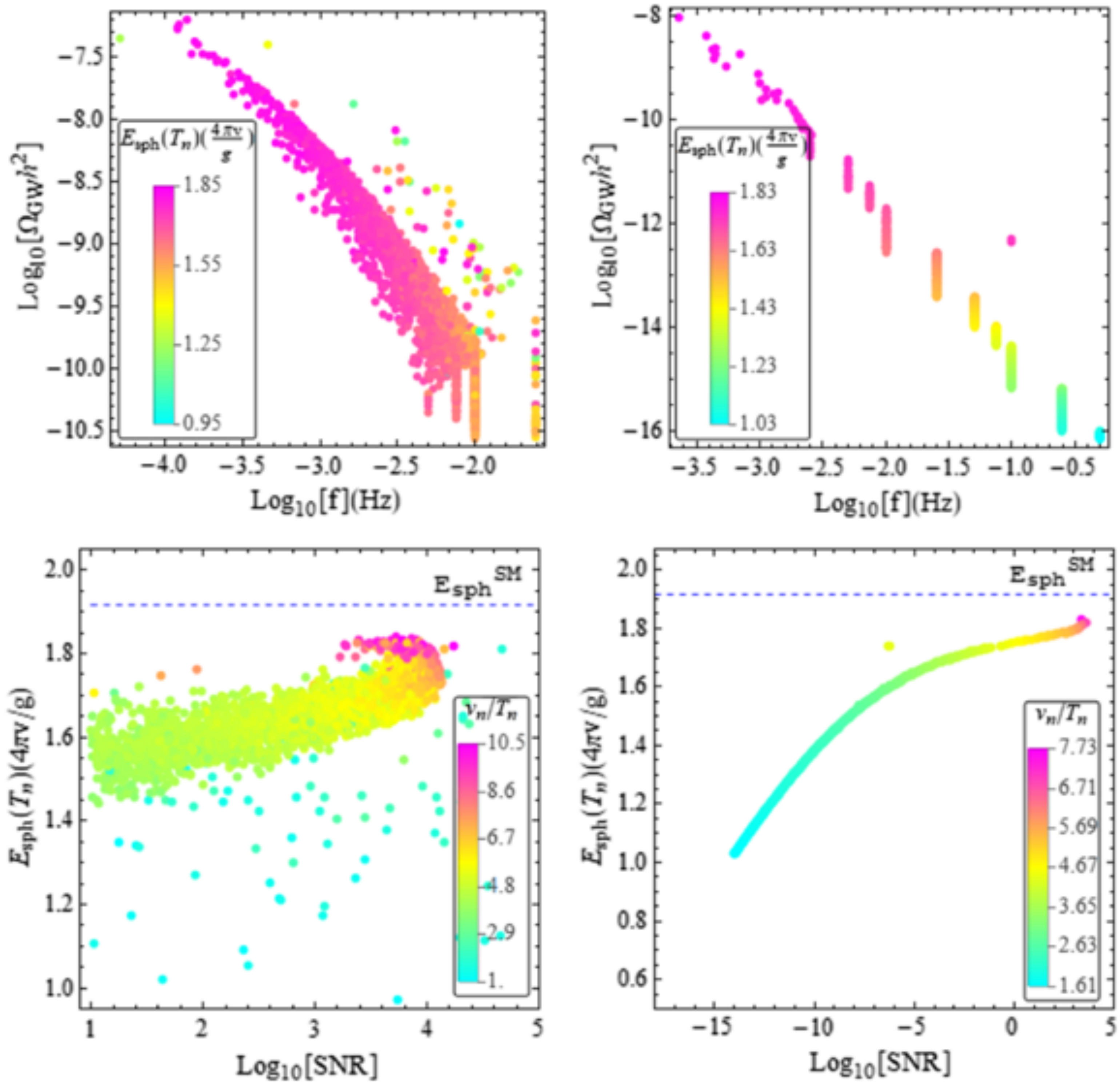
$$\Delta B = N_F(\Delta N_{CS} - \Delta n_{CS}),$$

$$N_{CS} = -\frac{g_2^2}{16\pi^2}\int d^3x\, 2\epsilon^{ijk}\,\mathrm{Tr}\left[\partial_i A_j A_k + i\frac{2}{3}g_2 A_i A_j A_k\right],$$

$$n_{CS} = -\frac{g_1^2}{16\pi^2}\int d^3x\, \epsilon^{ijk}\,\partial_i B_j B_k,$$

Sphaleron with GW

xSM & SMEFT



Zhou, **Bian***, Guo*, Phys.Rev.D 101 (2020) 091903(R)

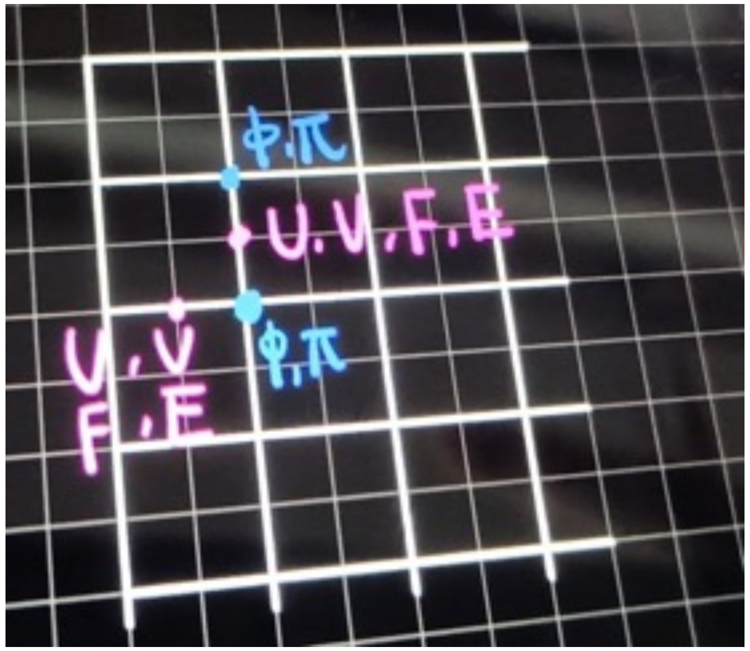
Lattice EW field foundation

$\Phi(t, x)$: Higgs field doublet defined on sites;

$U_i(t, x)$ and $V_i(t, x)$: SU(2) and U(1) link fields, defined on the link between the neighboring sites x and x + i , $\Phi(t, x)$, $U_i(t, x)$ and $V_i(t, x)$ are defined at time steps $t + \Delta t, t + 2\Delta t, \ldots$;

Conjugate momentum fields: $\Pi(t+\Delta t/2, x)$, $F(t+\Delta t/2, x)$ and $E(t+\Delta t/2, x)$, are defined at time steps $t + \Delta t/2, t + 3\Delta t/2$.

$$U_i(t,x) = \exp\left(-\frac{i}{2} g \Delta x \sigma^a W_i^a\right)$$
$$U_0(t,x) = \exp\left(-\frac{i}{2} g \Delta t \sigma^a W_0^a\right)$$
$$V_i(t,x) = \exp\left(-\frac{i}{2} g \Delta x B_i\right)$$
$$V_0(t,x) = \exp\left(-\frac{i}{2} g \Delta t B_0\right).$$



$$D_i\Phi = \frac{1}{\Delta x}\left[U_i(t,x)V_i(t,x)\Phi(t,x+i) - \Phi(t,x)\right]$$
$$D_0\Phi = \frac{1}{\Delta t}\left[U_0(t,x)V_0(t,x)\Phi(t+\Delta t,x) - \Phi(t,x)\right].$$

$$\Phi(t+\Delta t, x) = \Phi(t,x) + \Delta t \Pi(t+\Delta t/2, x)$$
$$V_i(t+\Delta t, x) = \frac{1}{2} g' \Delta x \Delta t E_i(t+\Delta t/2, x) V_i(t,x)$$
$$U_i(t+\Delta t, x) = g \Delta x \Delta t F_i(t+\Delta t/2, x) U_i(t,x),$$

Temporal gauge
$U_0(t, x) = I_2$, $V_0(t, x) = 1$

leapfrog

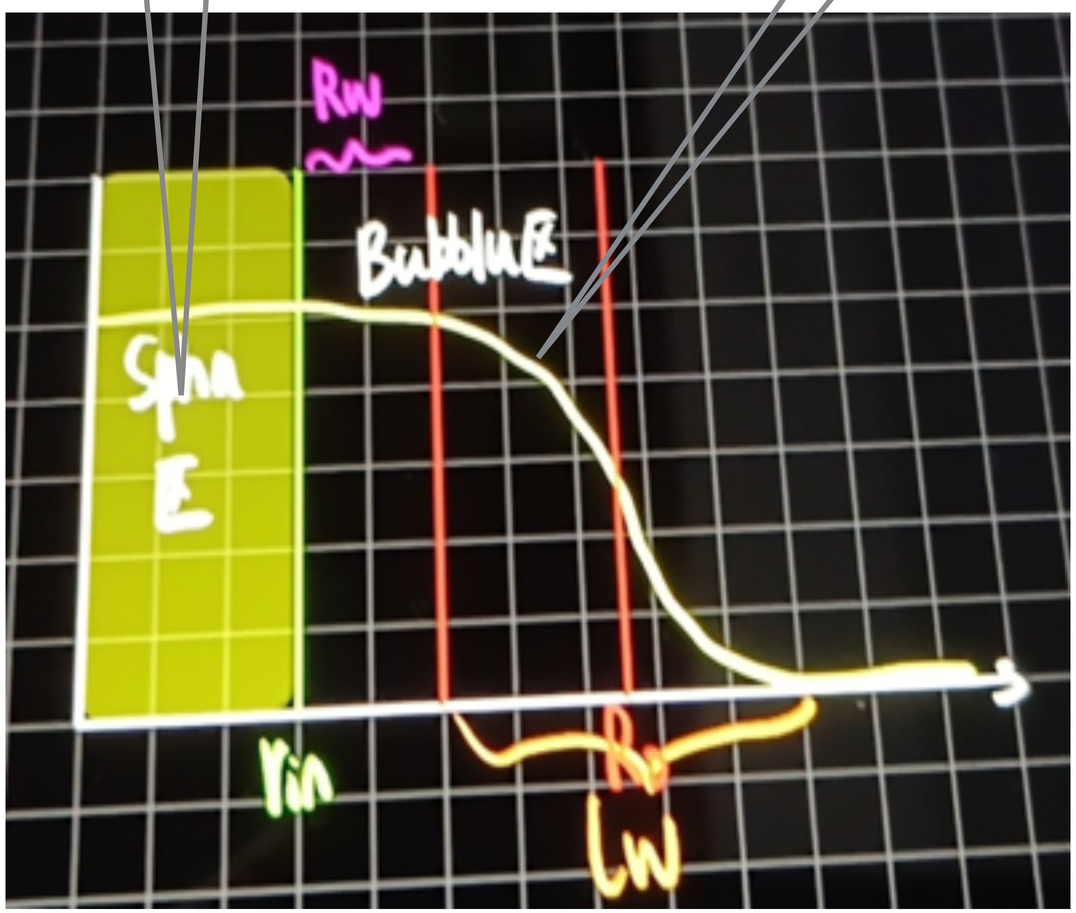
Bubble with sphaleron

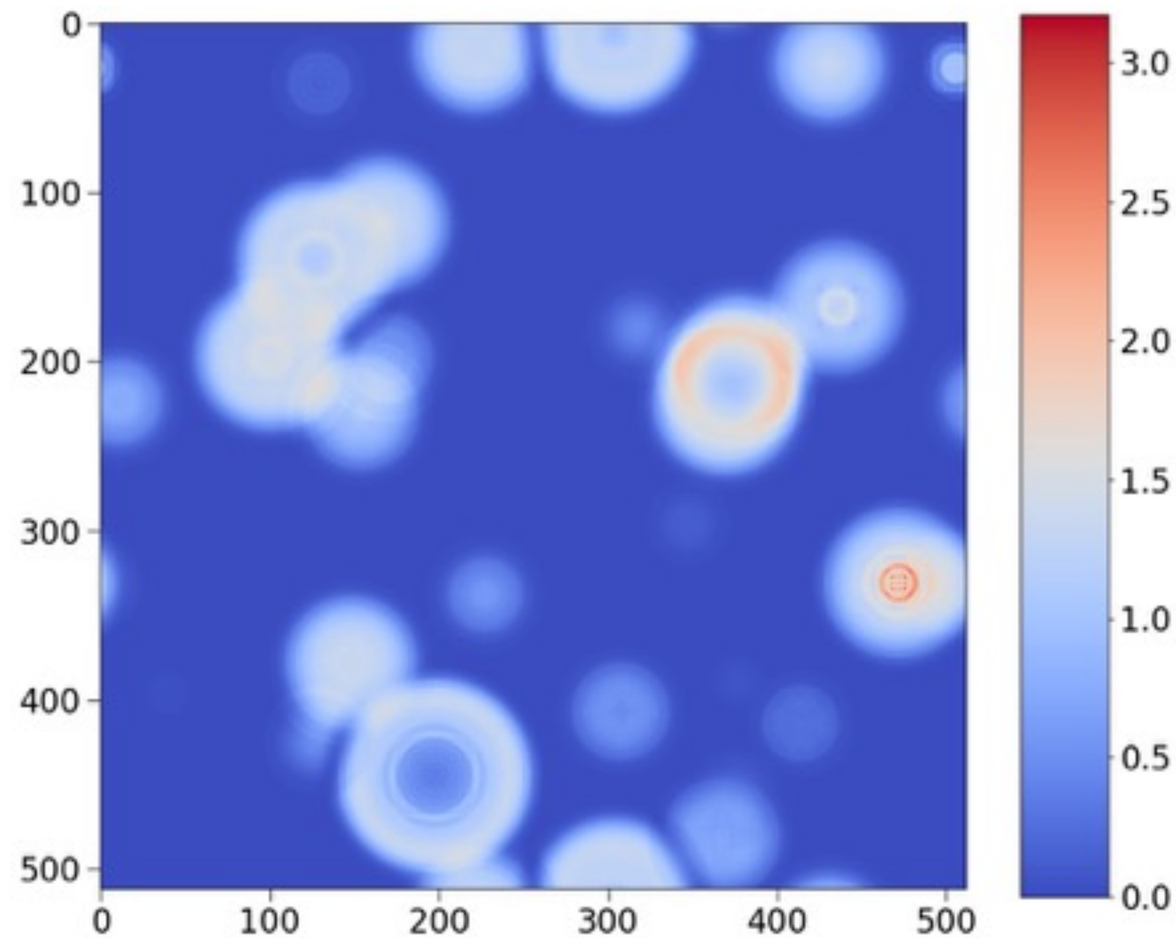
$$\Phi = \frac{v h(\xi)}{r} \begin{pmatrix} ix + y \\ -iz \end{pmatrix}$$

$$W_i^a \tau^a = -\frac{2 f(\xi)}{g r^2} \epsilon_{icb} x_b \mathbf{G}_\Theta \tau^c \mathbf{G}_\Theta^\dagger$$

$$\mathbf{G}_\Theta(\vec{x}) = \exp\left[i\Theta(r) \boldsymbol{\tau} \cdot \hat{\mathbf{x}}/2\right]$$

$$\phi_c(r) = \frac{\phi_b}{2}\left[1 - \tanh\left(\frac{r - R_c^{tw}}{l_0^{tw}}\right)\right]$$



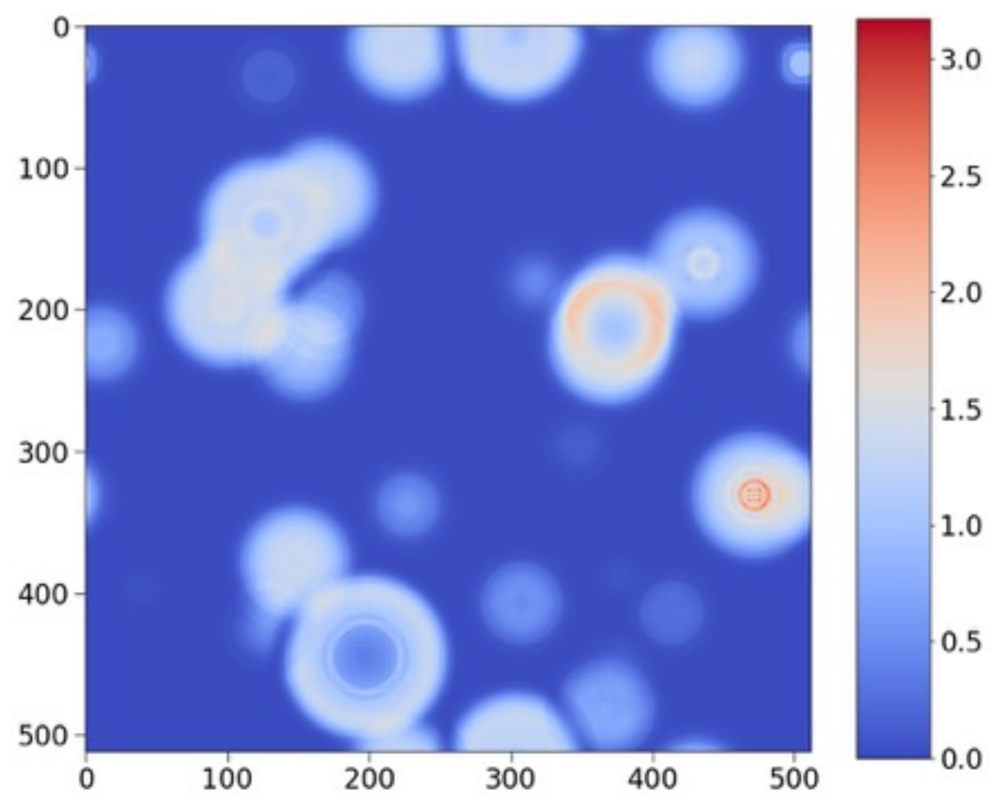


Di, Wang, Zhou, **Bian***, Cai*,Liu*, Phys.Rev.Lett. 126 (2021) 251102

Field basis

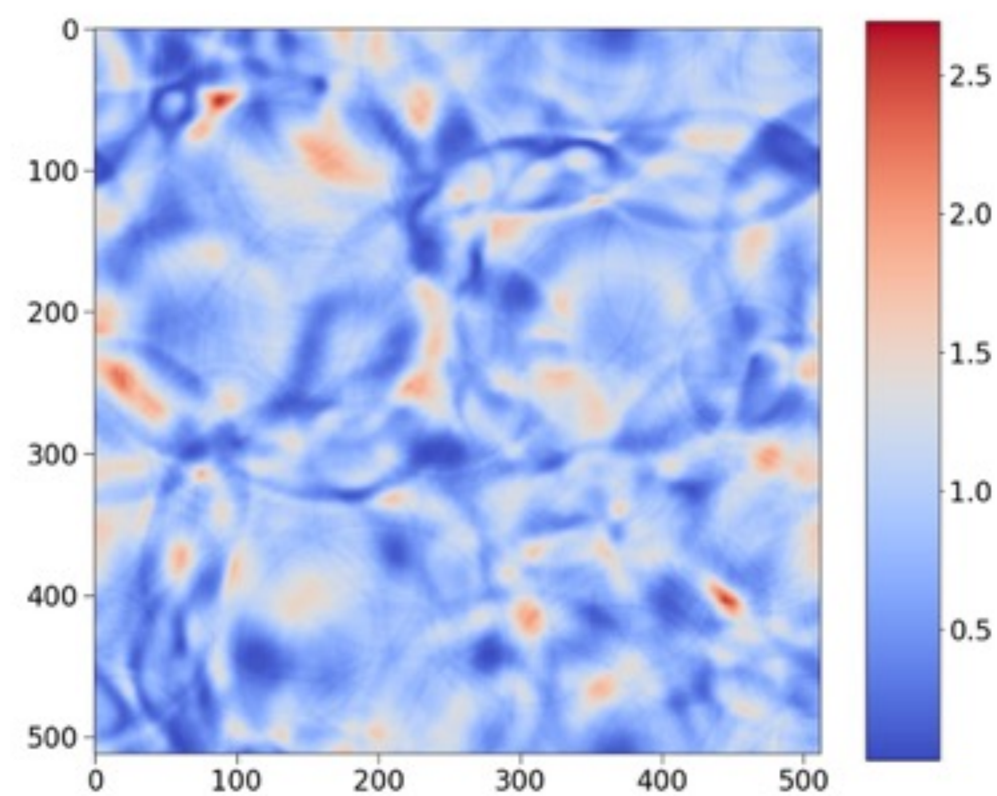
$$\begin{aligned}
\partial_0^2\Phi &= D_i D_i \Phi - 2\lambda(|\Phi|^2 - \eta^2)\Phi - 3(\Phi^\dagger\Phi)^2\Phi/\Lambda^2, \\
\partial_0^2 B_i &= -\partial_j B_{ij} + g'\,\mathrm{Im}[\Phi^\dagger D_i \Phi], \\
\partial_0^2 W_i^a &= -\partial_k W_{ik}^a - g\,\epsilon^{abc} W_k^b W_{ik}^c + g\,\mathrm{Im}[\Phi^\dagger \sigma^a D_i \Phi].
\end{aligned}$$

$$\partial_0\partial_j B_j - g'\,\mathrm{Im}[\Phi^\dagger \partial_0 \Phi] = 0,$$
$$\partial_0\partial_j W_j^a + g\,\epsilon^{abc} W_j^b \partial_0 W_j^c - g\,\mathrm{Im}[\Phi^\dagger \sigma^a \partial_0 \Phi] = 0.$$



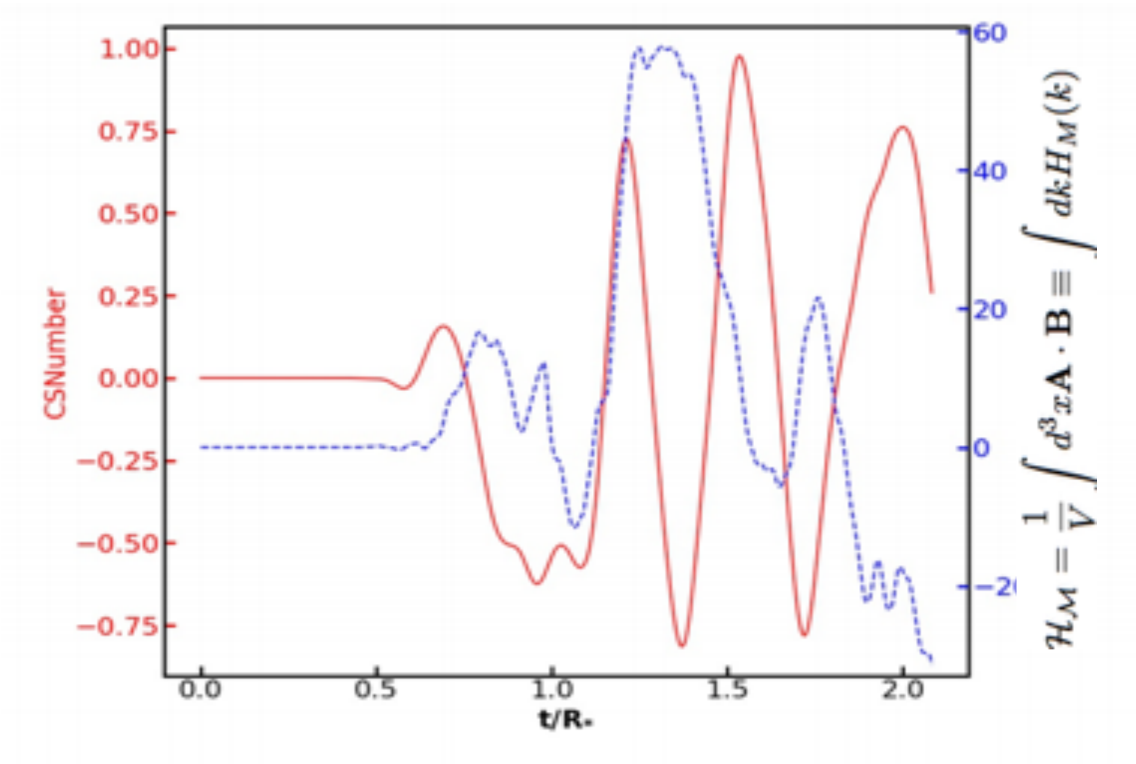
Lattice implementation

$$\begin{aligned}
\Pi(t+\Delta t/2,x) =& \Pi(t-\Delta t/2,x) + \Delta t\Big\{\frac{1}{\Delta x^2}\sum_i [U_i(t,x)V_i(t,x)\Phi(t,x+i) \\
&- 2\Phi(t,x) + U_i^\dagger(t,x-i)V_i^\dagger(t,x-i)\Phi(t,x-i)] - \frac{\partial U}{\partial \Phi^\dagger}\Big\} \\
\mathrm{Im}[E_k(t+\Delta t/2,x)] =& \mathrm{Im}[E_k(t-\Delta t/2,x)] + \Delta t\Big\{\frac{g'}{\Delta x}\mathrm{Im}[\Phi^\dagger(t,x+k)U_k^\dagger(t,x)V_k^\dagger(t,x)\Phi(t,x)] \\
&- \frac{2}{g'\Delta x^3}\sum_i \mathrm{Im}[V_k(t,x)V_i(t,x+k)V_k^\dagger(t,x+i)V_i^\dagger(t,x) \\
&+ V_i(t,x-i)V_k(t,x)V_i^\dagger(t,x+k-i)V_k^\dagger(t,x-i)]\Big\} \\
\mathrm{Tr}[i\sigma^m F_k(t+\Delta t/2,x)] =& \mathrm{Tr}[i\sigma^m F_k(t-\Delta t/2,x)] + \Delta t\Big\{\frac{g}{\Delta x}\mathrm{Re}[\Phi^\dagger(t,x+k)U_k^\dagger(t,x)V_k^\dagger(t,x)i\sigma^m\Phi(t,x)] \\
&- \frac{1}{g\Delta x^3}\sum_i \mathrm{Tr}[i\sigma^m U_k(t,x)U_i(t,x+k)U_k^\dagger(t,x+i)U_i^\dagger(t,x) \\
&+ i\sigma^m U_k(t,x)U_i^\dagger(t,x+k-i)U_k^\dagger(t,x-i)U_i(t,x-i)]\Big\},
\end{aligned}$$

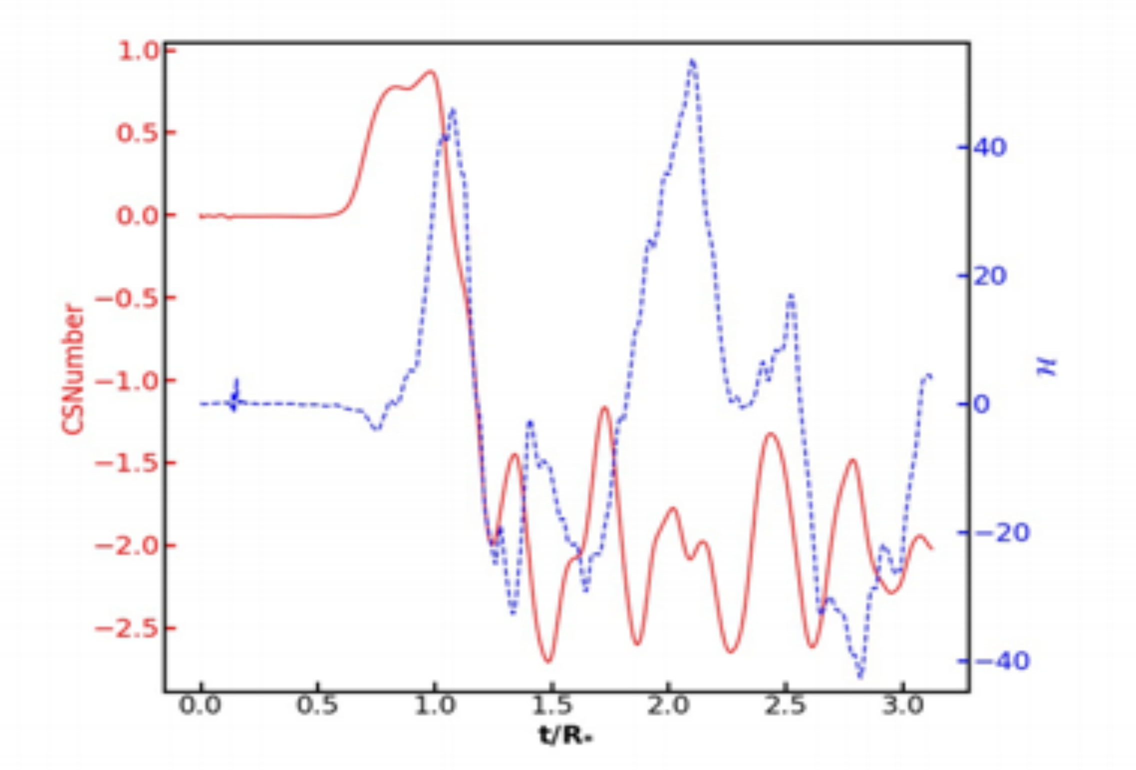


Di, Wang, Zhou, **Bian***, Cai*,Liu*, Phys.Rev.Lett. 126 (2021) 251102

CS number and the magnetic helicity

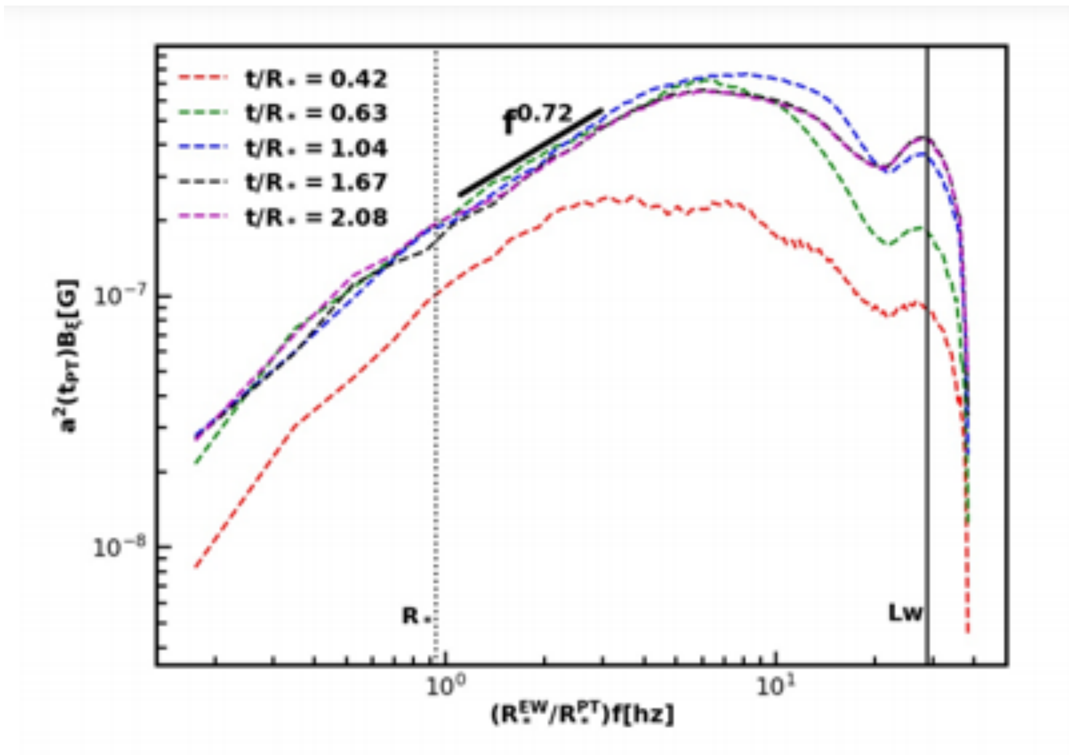


Without sphaleron, the CS number oscillates around zero throughout the PT process.



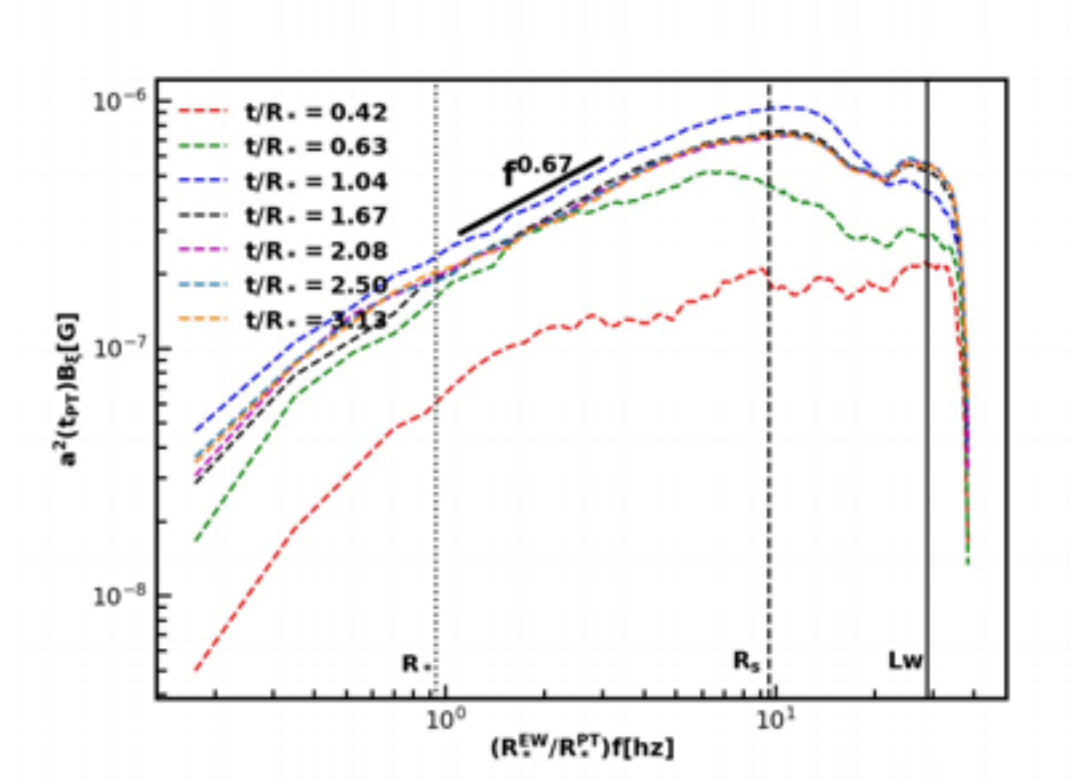
B + L anomaly: ΔNB = 3 ΔNCS~3 ;
Magnetic helicity and NCS: |H|~18ΔNCS~ 6ΔNB.

Di, Wang, **Bian***, Cai*, Liu*, 2107.08978



Non-vanishing gradients of the Higgs fields can generate magnetic fields when bubbles collide

$$A_{\mu\nu} = \sin\theta_w n^a W^a_{\mu\nu} + \cos\theta_w B_{\mu\nu} - i\frac{2}{gv^2}\sin\theta_w \left[(D_\mu\Phi)^\dagger(D_\nu\Phi) - (D_\nu\Phi)^\dagger(D_\mu\Phi)\right].$$



$$\langle B_i^*(\boldsymbol{k},t)B_j(\boldsymbol{k}',t)\rangle = (2\pi)^3\delta^{(3)}(\boldsymbol{k}-\boldsymbol{k}')F_{ij}(\boldsymbol{k},t)$$

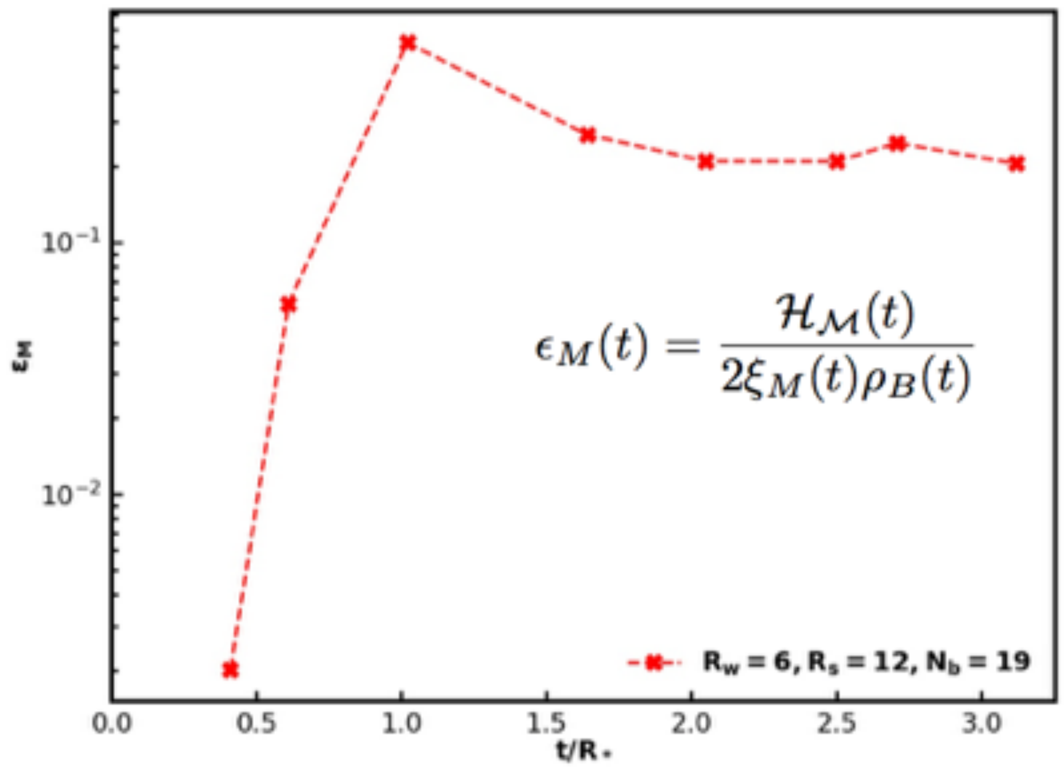
$$F_{ij}(\boldsymbol{k},t) = (\delta_{ij} - \hat{k}_i\hat{k}_j)E_M(k,t)/(4\pi k^2) + i\epsilon_{ijl}k_l H_M/(8\pi k^2)$$

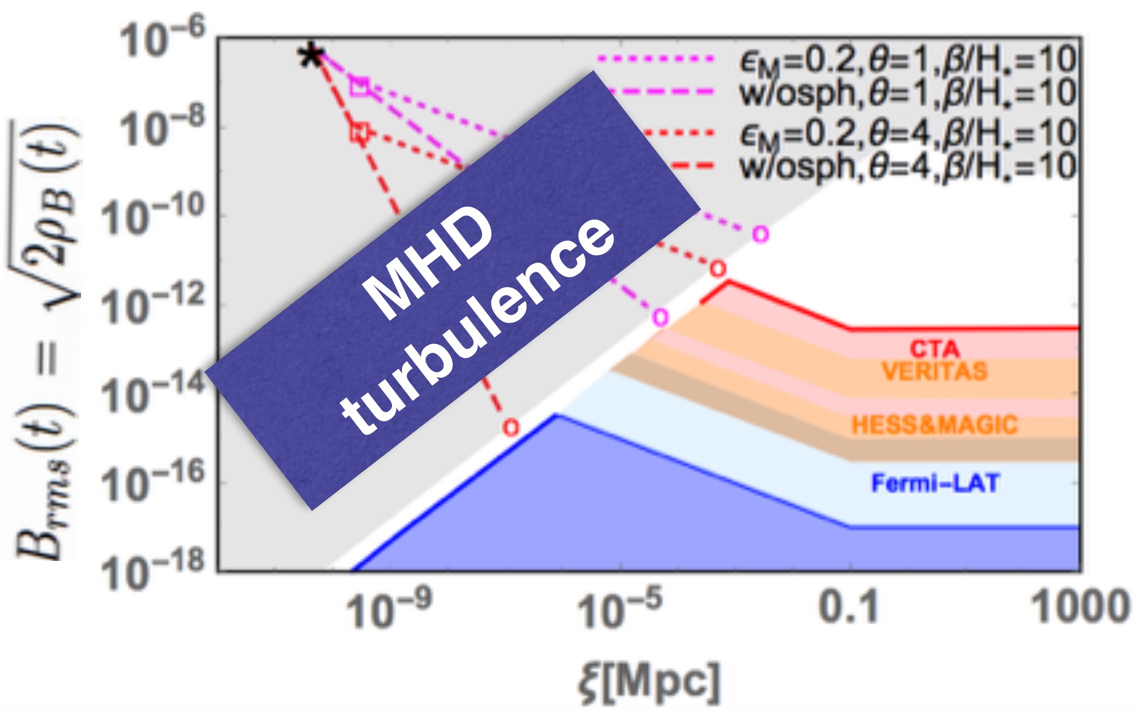
$$\rho_B(t) = \int_0^\infty E_M(k,t)\,dk$$

$$B_\xi = \sqrt{2 d\rho_B/d\log(k)} \quad \xi_M(t) = \int dk k^{-1} E_M(k,t)/\rho_B(t)$$

Di, Wang, **Bian***, Cai*, Liu*, 2107.08978

MF versus Sphaleron





MF helicity evolution with PT proceeding

$$\Phi = \frac{vh(\xi)}{r}\begin{pmatrix} ix+y \\ -iz \end{pmatrix}$$

$$W_i^a\tau^a = -\frac{2f(\xi)}{gr^2}\epsilon_{icb}x_b\mathbf{G}_\Theta\tau^c\mathbf{G}_\Theta^\dagger$$

$$\mathbf{G}_\Theta(\vec{x}) = \exp[i\Theta(r)\boldsymbol{\tau}\cdot\hat{\mathbf{x}}/2]$$

Cosmic-ray and gamma ray observations can tell the helicity of the MF

Di, Wang, **Bian***, Cai*, Liu*, 2107.08978

Summary and future

Observation of the cosmic Magnetic field seeded by phase transition with GW production may hint the B+L violation

Interaction between bubble wall and Plasma, and interaction among different bubbles are important for Baryogenesis during PT

Higgs Potential shape

1) **The future collider prospect, with dihiggs, Zh and/or Zhh production**
2) **Thin wall or thick wall tell by gravitational wave, wall profile and GW spectrum**

CPV @Colliders & EDMs

Thanks

CPV and EDMs

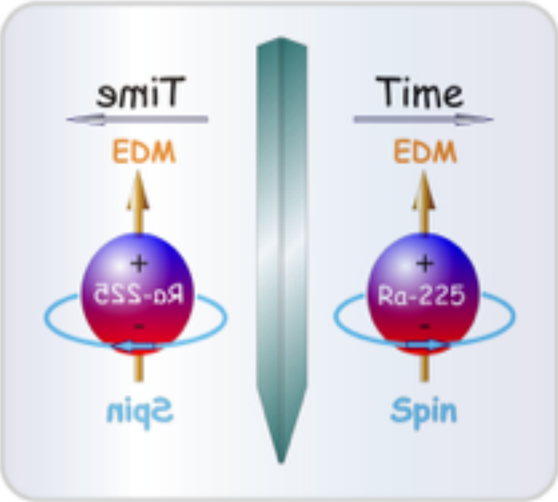


Figure 1-1. *The interaction of an elementary particle EDM with an electric field violates time-reversal symmetry. When time is reversed, the spin is reversed, and so is the elementary particle EDM. The EDM of a classical system that corresponds to a spatial charge separation (denoted by "EDM" in the figure) does not reverse. Thus, the classical EDM interaction in a time-reversed world looks the same as in the original world, while the elementary particle EDM interaction does not.*

Table 1-1. *Upper limits on EDMs in three different categories. Note that the limit on the electron EDM from the ThO molecule assumes that only the EDM of the electron would contribute to a signal. In a model independent analysis, the ThO limit constrains a linear combination of the electron EDM and a CP-violating semileptonic interaction (see, e.g., Ref. [3]).*

Category	EDM Limit ($e\cdot$cm)	Experiment	Standard Model value ($e\cdot$cm)
Electron	8.7×10^{-29}	ThO molecules in a beam [12]	10^{-38}
Neutron	2.9×10^{-26}	Ultracold neutrons in a bottle [11]	10^{-31}
Nucleus	3.1×10^{-29}	^{199}Hg atoms in a vapor cell [13]	10^{-33}

$|d_{\rm Hg}/e| < 7.4 \times 10^{-30}$cm (red) B. Graner, et al, Phys. Rev. Lett. 116, no. 16, 161601 (2016)

The future Ra225 would improve the EDM measurements by 2 ~3 orders of magnitudes, 10^-28.

arXiv:1312.5416 [hep-ph]. arXiv:1606.04931 [nucl-ex].